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Time-of-Flight Based Sonic Speed Measurements for Cold Gas Thruster Development

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The purpose of this thesis is to explore an experiment developed for validating the usage of a gaseous solution of water and propylene glycol for cold gas propulsion. The experiment involves a "Time of Flight" method of calculating the speed of sound in the gas and the corresponding specific heat ratio using a copper tube, two MEMS microphones, a piezoelectric speaker, and data-acquisition hardware. The experiment was calibrated using the known thermodynamic properties of air. The accuracy of the experiment was found to be within 0.6% for calculations of the speed of sound in air and within 1.0% of the specific heat ratio of air. This experiment can be used to determine the specific heat ratio of any gas placed inside the tube, which will allow for the usability of the gas as a cold gas propellant to be verified.

Table of Contents

INTRODUCTION

The development of CubeSats has become increasingly popular among universities in the United States over the last fifteen years. CubeSats have a low mass, usually between 1.33 kg and 4.00 kg, meaning that they can be put into orbit much easier than a full-sized spacecraft[1]. Once a CubeSat is in orbit, its maneuverability depends on its onboard propulsion system. Cold gas thrusters are a popular choice for miniaturized spacecraft, as these thrusters operate on low power and allow for precise attitude control with micronewton-level thrust[2]. Microresistojets, on the other hand, offer a higher specific impulse than that of a cold gas thruster of equivalent size but require a heater, thus consuming more power[3].

One proposed type of cold gas thruster involves the storage and subsequent throttling of a pre-mixed liquid water and propylene glycol solution[4]. A mixture of these two chemicals results in a safe, nonvolatile option for propellant choice[5]. Propylene glycol acts as a freezing point depressant in this solution so that the water will not freeze when its storage tank is in orbit onboard a CubeSat[6]. An aqueous solution of propylene glycol has not been used as a CubeSat propellant before, and as such its usability as a propellant is unknown. To test the potential effectiveness of a propellant consisting of water and propylene glycol, the specific impulse of a thruster using this propellant must be calculated. The specific impulse of a thruster measures how much thrust is generated per unit mass of propellant consumed[7]. This value is a measure of the efficiency of a thrust engine, and as such it is useful in predicting the performance of said thruster.

As the goal of this research is to test the usability of a safe, aqueous propylene glycol solution as a cold gas system propellant, we must first analyze the claim that it would be a viable option based on its thermodynamic properties alone. Figure 2 suggests that hydrogen would be the ideal candidate for a propellant, as the ideal specific impulse of a thruster utilizing hydrogen is about 300 s; however, hydrogen is highly dangerous to handle due to its flammability. Helium would be the next choice in this search for a propellant with a high, ideal specific impulse, but helium must be stored in a larger tank volume or at a high pressure, thus adding to the cost of a cold gas propulsion system[12]. Methane, with the next-highest ideal specific impulse, is also flammable, and ammonia is toxic to humans[13]. Water vapor, then, offers the highest specific impulse of what is considered to be a safe option for a propellant. It is currently unknown how the addition of propylene glycol to water vapor will impact the specific heat ratio of the solution.

This research aims to predict the performance of a thruster utilizing an aqueous solution of propylene glycol based on the theoretical specific impulse this thruster could deliver. In this paper, we investigate an experiment developed for the purpose of determining the specific heat ratio of a water and propylene glycol solution. At the time of writing this paper, mixtures of water vapor and propylene glycol have not yet been tested. Due to time constraints, the experimental assembly has been configured only for experimentation with air.

THEORY

When designing a cold gas propulsion system, it is useful to know the maximum specific impulse achievable by utilizing a certain propellant. The specific impulse of an ideal, isentropic, compressible flow nozzle is given by the equation[8]

$$I_{sp} = \frac{1}{g_0}\sqrt{\frac{kR_uT}{M}}\left[\left(\frac{2}{k+1}\right)^{-\frac{k+1}{2k-2}}\right]\left[\left(\frac{2}{k-1}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right]^{\frac{1}{2}} \tag{1}$$

where I_{sp} is specific impulse, g_0 is the acceleration due to gravity, k is the specific heat ratio, R_u is the universal gas constant, T is the temperature of the fluid, and M is molecular weight. The specific impulse calculated with this equation is the theoretical maximum specific impulse achievable by a thruster operating in a vacuum and utilizing a propellant of molecular weight, M, and specific heat ratio of magnitude k.

The specific heat ratio of a fluid, also known as the *adiabatic index*, is the ratio of its specific heat at constant pressure to its specific heat at constant volume[9]. The specific heat ratio of a gas is related to the speed of sound in the gas by the equation[10]

$$a = \sqrt{\frac{kR_uT}{M}} \tag{2}$$

where a is the speed of sound, and the remaining variables are defined similarly as before. Sonic velocities can be recorded by measuring the time it takes for a sound wave to travel a fixed distance from one location to another. This method of experimentation is often referred to as a "Time of Flight" method, and an experiment involving the measurement of a sound wave travelling from one microphone to another would achieve this goal. For an experiment that uses data acquisition hardware to record a sound wave moving one-dimensionally from one microphone to another, the speed of sound is given by

$$a = \frac{L*f}{\Delta S} \tag{3}$$

where L is the distance between the two microphones, f is the sampling rate, and S is a sample number corresponding to the output voltage of a microphone. The sample differential, ΔS, refers to the difference in sample numbers corresponding to a similar voltage readout of both microphones. In other words, there is a slight phase shift between the voltage responses of the two microphones, and the sample differential quantitatively expresses this phase shift in terms of time. Substituting Eq. (2) into Eq. (1) and solving for k yields

$$k = \frac{M}{R_u T}\left(\frac{L * f}{\Delta S}\right)^2 \tag{4}$$

The specific heat ratios for various gases are plotted against their respective molecular weights in Fig. 1[9]. It can be observed from this plot that the specific heat ratio tends to decrease as the molecular weight of a gas increases.

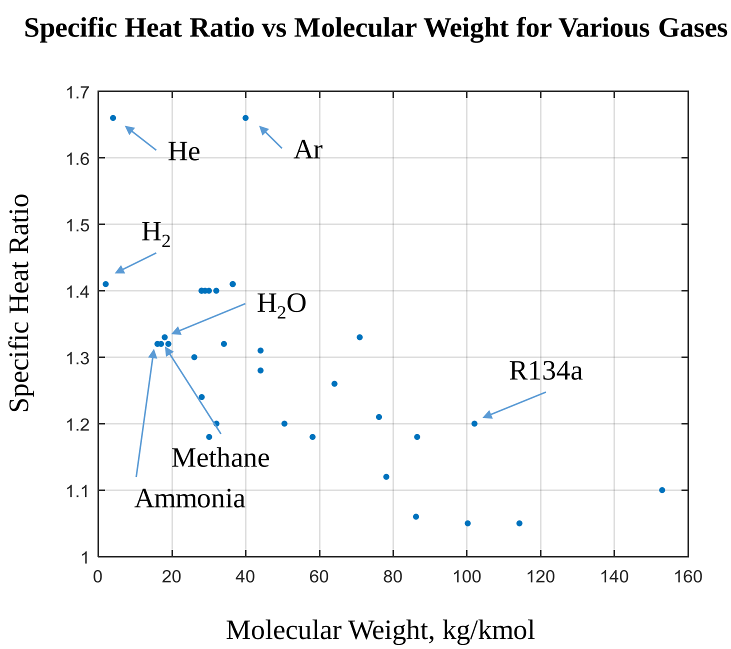

Figure 1. Specific heat ratio as a function of molecular weight

The theoretical specific impulses of a thruster utilizing these same gases as propellants are plotted in Fig. 2 with respect to k as per Eq. 1. From Fig. 1 and Fig. 2, it can be seen that gases with a low molecular weight and specific heat ratio larger than 1.3 tend to allow for a high specific impulse. The viability of a gas to be used as a propellant depends on both its specific heat ratio and its molecular weight. The effect of the molecular weight on the viability of a propellant can be seen prominently in the case of helium and argon. As seen in Fig. 2, though helium and argon both have a specific heat ratio of 1.66, a helium-based propulsion system offers an ideal specific impulse three times larger than that of argon. Since argon has a higher molecular weight than helium, its viability as a propellant is diminished. R134a, a popular choice for cold gas propulsion in CubeSats, has a high molecular weight and a low specific heat ratio, and as Fig. 2 suggests, its specific impulse is among the lowest of the gases considered in this analysis[11].

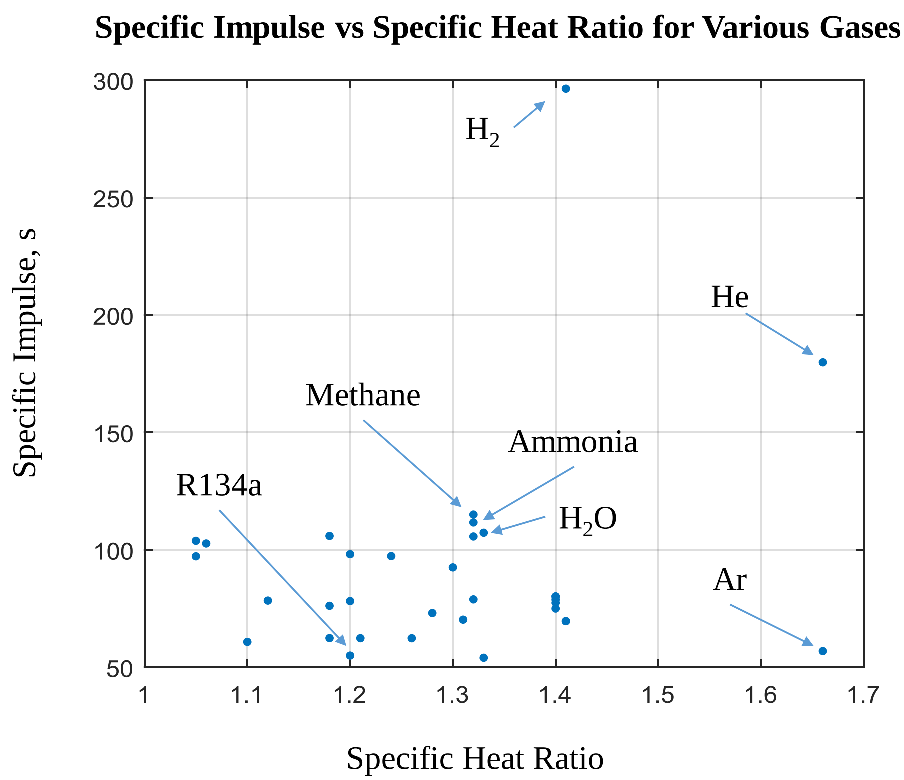

Figure 2. Ideal specific impulse as a function of specific heat ratio

INSTRUMENTATION AND EQUIPMENT

This experiment is based on another sonic velocity experiment that utilizes an apparatus known as a Kundt's tube[14]. For the purposes of this research, the standard Kundt's tube apparatus is not feasible because the speed of sound needs to be measured at different pressures. If a glass tube were to be used, as is the case for a typical Kundt's tube, it could sustain damage at near-vacuum pressures. This experiment therefore uses a copper tube connected to three tee fittings, thus allowing for five separate entry points to the inside of the tube. As is the case in the Kundt's tube apparatus, one end of this copper tube houses a mini-piezoelectric speaker that points horizontally along the length of the tube. The speaker is pictured in Fig. 3. A sound wave is produced from the speaker via LabVIEW and data-acquisition hardware. For preliminary tests at atmospheric pressure, the tube and its various fittings were not sealed so that the equipment could be calibrated properly and replaced as necessary. When it came time to conduct experiments at lower pressures, the pipe fittings were sealed using Teflon tape, and the microphones were sealed in steel tubing using epoxy as pictured in Fig. 4.

Since the inside of the tube is not observable, two MEMS microphones are inserted in two of the vertical entry points to record the sound wave as it travels through the tube. The voltage responses of the speaker and the two microphones are recorded by the same data-acquisition hardware that generates the sound wave. The third vertical entry point is connected to the vacuum pump and also branches off to a pressure sensor so that the pressure inside the tube may be read. The end of the copper tube connected to the pressure sensor is seen in Fig. 5. The pressure is controlled by adjusting a needle valve connected to the vacuum pump line as pictured in Fig. 6. The vacuum pump can be seen in Fig. 7. The fifth entry point, directly opposite of the end containing the speaker, is capped off for all tests performed with air. This entry point will be replaced by a supply line through which a gas desired for experimentation may flow. The full assembly may be seen in Fig. 8.

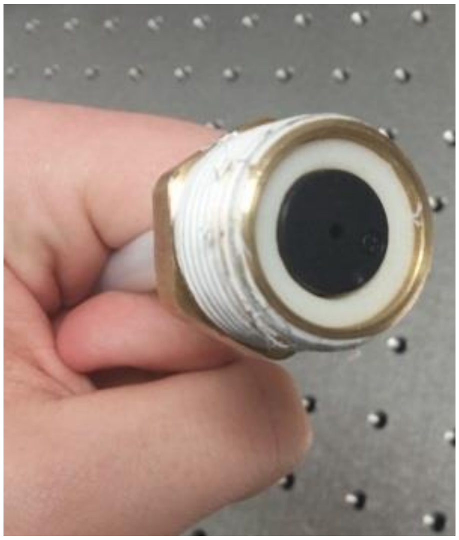

Figure 3. Speaker inside pipe fitting

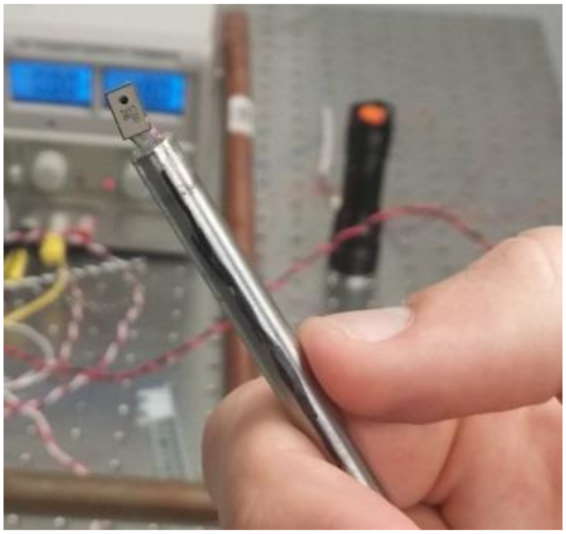

Figure 4. Microphone sealed inside steel tubing

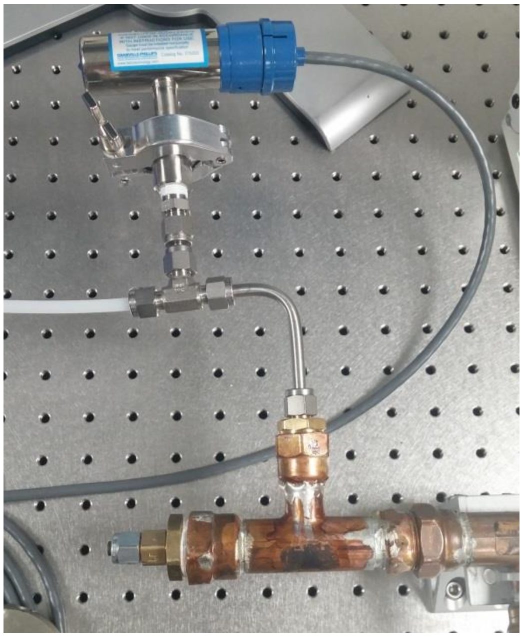

Figure 5. Pressure sensor junction

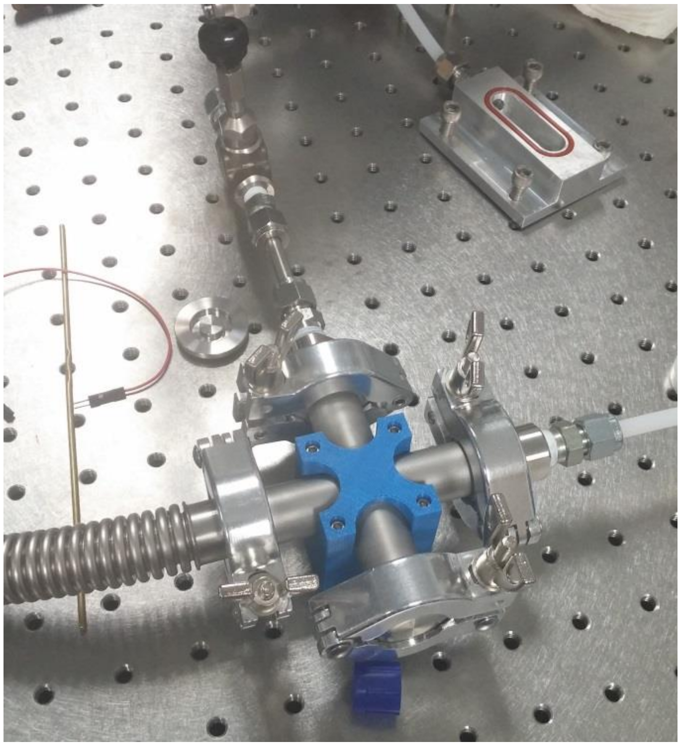

Figure 6. Vacuum line junction with needle valve

Figure 7. Vacuum pump

Figure 8. Full experimental assembly

Equipment List

- 1x 7/8” OD Copper Tube
    - Length = 22.5”
    - Silver-brazed with one 1” x 7/10” x 1” tee fitting at each end
- 2x Knowles Acoustics SiSonic microphones
    - Model No. SP01013NC3-3
- 1x 1” x 7/10” x 1” tee fitting
- 2x 3/8” OD Tube x 1” MIP BrassCraft Compression Fitting
- 3x 1/4” OD Tube x 1/2” MIP BrassCraft Compression Fitting
- 1x MASTECH DC Power Supply HY3002D-2
- 1x National Instruments SCB-68 Data-Acquisition Device
- 1x RadioShack Technology 12V_{DC} Piezo Mini Buzzer
    - 3.0-16 V_{DC}, 4.1 kHz, 7 mA
    - Model No. 273-074
- 2x 1 µF Tantalum Capacitors
- 2x 1 kΩ Resistors
- 2x 10 kΩ Resistors
- 1x 5.1 kΩ Resistor
- 1x ZTX601 Transistor
- 1x Springfield PreciseTemp Thermometer
- 1x AD623 Instrument Amplifier
- 2x 0.25” OD Steel Tubes
    - Length = 7.5”
- 1x Edwards 1.5 E2M1.5 Rotary Vane Vacuum Pump
- 1x Granville-Phillips 475 Convectron Pressure Sensor
- Loctite M-121HP Hysol Epoxy Adhesive
- PTFE Thread Seal Tape
    - MIL SPEC T-27730A
    - 1/2” x 520”
- Software
    - NI LabVIEW 2015
    - MATLAB R2015a
    - SolidWorks 2015 x64 Edition
    - Microsoft Excel 2013
    - Windows 8

PROCEDURE

The following procedure was utilized for all experimentation:

1. Turn on the voltage source and set to 18.0 V
2. Initialization step using *Gain Control.vi*
    a. Establish properties of sound wave
        i. Frequency = 440 Hz
        ii. Duty Cycle = 0.5
    b. Set the input voltage of the speaker to 5.0 V
    c. Abort the program
    d. Refer to Figure A.1 for the block diagram of this program
3. Experimentation using *Time of Flight v8.vi*
    a. Input the sound wave properties established in Step 2
    b. Set the number of pulses to 10
    c. Set the sampling rate to 400 kS/s
    d. Run the program
    e. Refer to Figure A.2 for the block diagram of this program
4. Post-processing step using *ea_full.m* script
    a. Convert the raw data file from a .lvm file to a .txt file
    b. Change the filename listed in line 6 of the MATLAB script to that of the previously-created LabVIEW data file
    c. Change the sampling rate in line 17 of the MATLAB script to that of the sampling rate utilized in Step 3
    d. Retrieve the speed of sound from this file
    e. Refer to Appendix B for the script used for post-processing
5. Specific heat ratio calculation
    a. Using the speed of sound found in Step 4 and the molecular weight of the gas, calculate the specific heat ratio using Eq. 4

RESULTS AND DISCUSSION

Experiments with air at pressures ranging from 149 torr to atmospheric pressure were conducted. The sound wave generated via LabVIEW had a frequency of 440 Hz, a duty cycle of 0.5, and lasted for 100 ms per pulse. The LabVIEW program was written to allow for up to 10 pulses of the sound wave to occur in rapid succession each time the program was run. The voltage data from the speaker and the two microphones were then processed in MATLAB. The MATLAB script performed an ensemble averaging process by averaging the voltage responses of the two microphones resulting from each pulse of the sound wave. This was done in order to reduce the noise of the signal received by each microphone so that the voltage data could be processed more efficiently. Figure 9 contains a sample plot of a full set of voltage data for all three components. The voltage of the speaker is pictured in yellow, and the voltages of the two microphones are shown in red and blue. When the speaker is inactive, its voltage rests at 0 V. When the speaker switches on to emit a sound wave, its voltage rises to approximately 5 V. Figure 10 shows the ensemble-averaged voltage responses for the two microphones after being processed by the MATLAB script.

Further data processing took place in the MATLAB script by calculating the speed at which the sound wave travelled in the tube. The time it took for the sound wave to travel from one microphone to the other is found by finding the number of samples recorded between corresponding voltage peaks of the two microphones. In Fig. 10, these two peaks are pointed out with arrows. This sample differential is then divided by the sampling rate to convert the sample differential into units of time. For all tests, a high sampling rate was desired. Thus, a sampling rate of 400 kHz was used. The speed of sound is then calculated by dividing the distance between the two microphones by this time delay as per Eq. 3. Placing this value into Eq. 4 along with the molecular weight of the gas, the temperature of the gas during data collection, and the universal gas constant allows for the specific heat ratio of the gas inside the tube to be calculated. Table1 contains a sample set of speed of sound and specific heat ratio determinations for experiments performed with air at atmospheric pressure. The experimental values for *a* and *k* are compared to their tabulated values at the recorded temperature.

At the time of writing this paper, the experimental setup is able to be pumped down to a pressure of 149 torr. At pressures of approximately 350 torr and 570 torr, the tube was observed to resonate when a 440 Hz sound wave was produced by the speaker. The speed of sound in air was calculated at various pressures. These values are recorded in Table 2. The lowest pressure at which the speed of sound was able to be calculated inside of the tube was 401 torr.

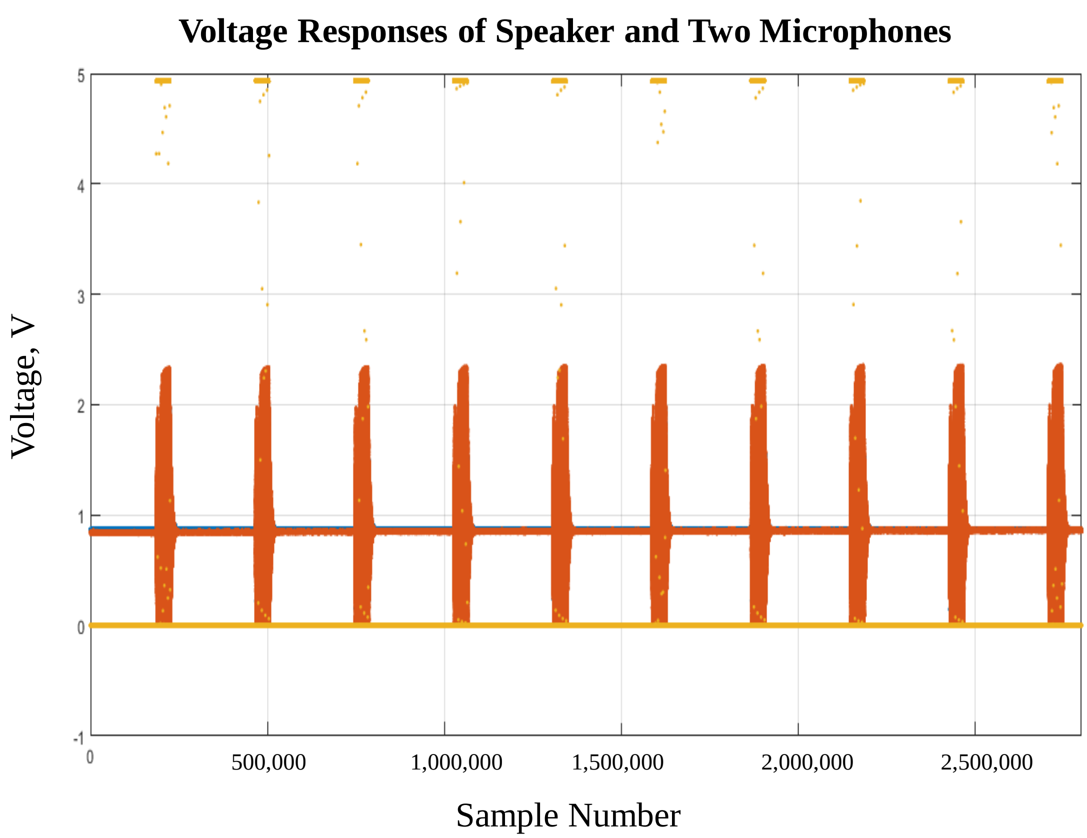

Figure 9. Full set of voltage responses for 10 pulses

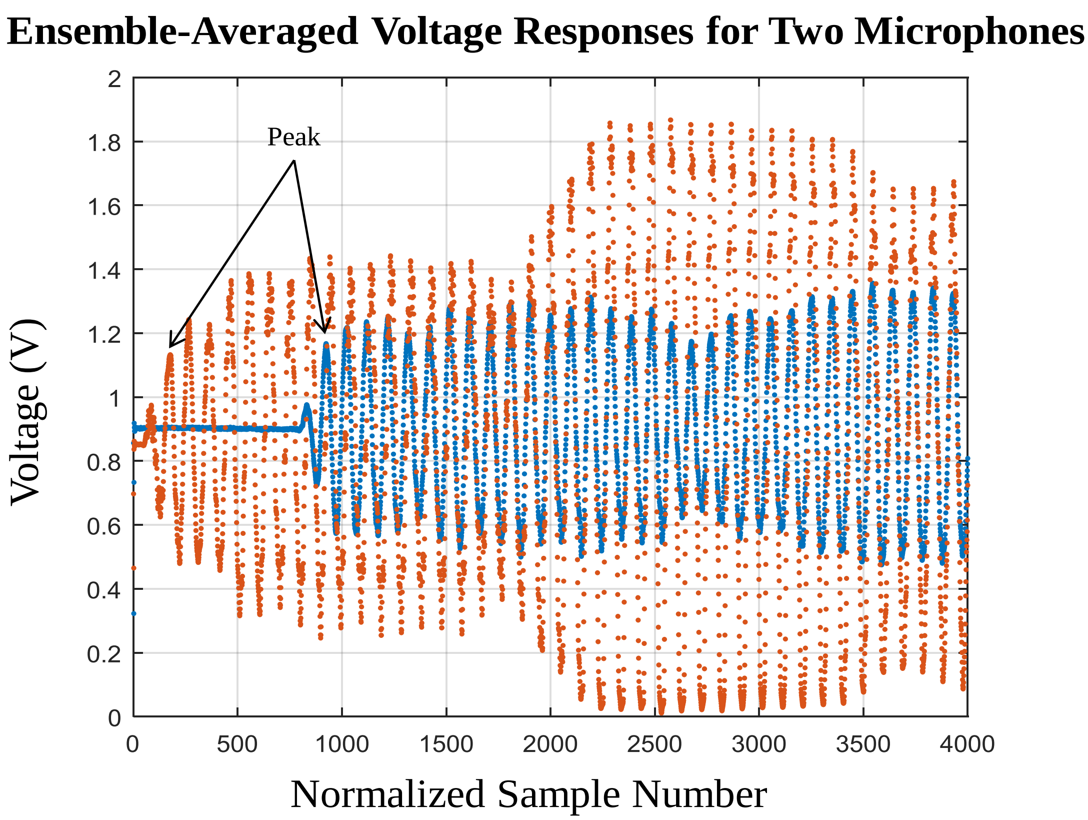

Figure 10. Ensemble average of microphone responses

Table 1. Experimentally-determined speeds of sound and specific heat ratios of air

Test Number	T, ^{0}C	ΔS	a, m/s	k	%Error, a	%Error, k
1	23.7	725	347.09	1.415	0.54%	1.02%
2	23.7	729	345.19	1.400	0.01%	0.09%
3	23.7	727	346.13	1.407	0.27%	0.46%
4	23.7	729	345.19	1.400	0.01%	0.09%
5	23.7	728	345.66	1.404	0.13%	0.19%
6	24.4	727	346.13	1.404	0.15%	0.23%
7	24.5	727	346.13	1.404	0.13%	0.19%
8	24.6	725	347.09	1.411	0.39%	0.71%
9	24.6	726	346.61	1.407	0.25%	0.43%
10	24.5	725	347.09	1.411	0.41%	0.75%

Table 2. Speeds of sound in air at various pressures

Test Number	P, torr	ΔS	a, m/s
1	401	730	344.71
2	411	727	346.13
3	435	727	346.13
4	438	725	347.09
5	446	730	344.71
6	466	719	349.99
7	496	730	344.71
8	524	720	349.50
9	545	728	345.66
10	577	732	343.77
11	599	727	346.13
12	603	729	345.19
13	640	743	338.68
14	649	733	343.30
15	782	729	345.19
16	784	725	347.09

The results validate that the experiment is able to measure the speed of sound in air within a reasonable margin. Sonic speeds ranging from 345.19 m/s to 347.09 m/s were measured at different temperatures resulting in error ranging from 0.01% to 0.54%. The corresponding specific heat ratios of air were determined to range from 1.400 to 1.415, and error ranged from 0.09% to 1.02%. These results were expected, as the data-acquisition hardware was sampling at the highest possible sampling rate, and sealing the tube prevented any outside influences from tampering with the air inside the tube. The speaker's ability to produce a continuous tone at low pressures was also expected, as there was still enough air inside the tube through which a sound wave could propagate. The auditory capacity of this tone decreased as the pressure lowered, which also corresponded to the expected results—as there was less air inside the tube, the compression of the air by the sound wave could not sustain its initial strength. I suspect that the audible resonance observed at 350 torr and 570 torr likely resulted from the shape of the air column within the tube at those particular pressures.

The tube was not able to be pumped down to a satisfactory pressure, achieving a lowest pressure of only 149 torr or 19.9 kPa. The water would have to be heated to a temperature of at least 60^0C in order for it to vaporize inside the tube[9]. It is likely that there are leaks in the current experimental assembly. The sources of these leaks are probably from the plastic tubing used in the vacuum pump line and the plastic tubing used to seal the end of the tube containing the speaker. As the pressure in the tube was decreased by the vacuum pump, I expected to see the speed of sound in air decrease. However, at pressures lower than 400 torr, the signals recorded by the microphones bore noise of a strength exceeding that of the sound wave travelling through the tube. Thus, the data were unable to be interpreted by MATLAB, and the sonic speeds at pressures lower than 400 torr could not be determined.

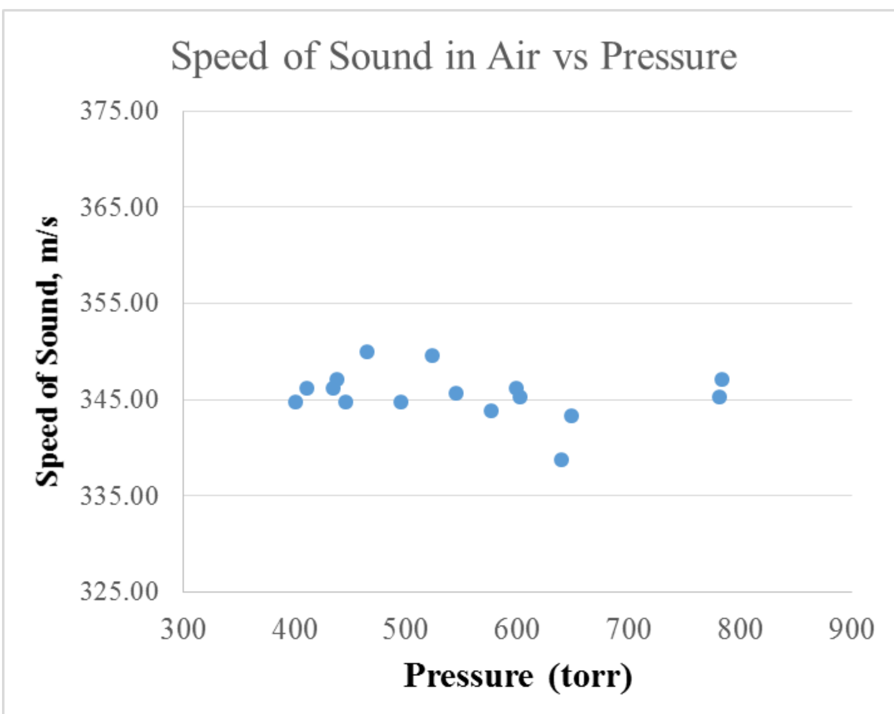

Figure 11: Plot of speeds of sound in air at various pressures

The process of removing air from the tube does not involve any heat transfer into or out of the tube, and the temperature of the tube itself remains steady. It can be expected, then, that the temperature of the air inside the tube will remain constant. Since the speed of sound in air is proportional to the square root of the temperature of the air, the speed of sound is expected to remain constant at lower pressures. As seen in Figure 11, the speed of sound in air was determined to remain fairly constant as the pressure decreases. Thus, the expected results were confirmed.

CONCLUSIONS AND RECOMMENDATIONS

In summary, the following goals were accomplished through this research:

- Developed an apparatus for measuring the speed of sound and specific heat ratio of various gaseous propellants.
- Measured the speed of sound in air and the corresponding specific heat ratio with <1.0% error.
- Measured the speed of sound at pressures between 400 torr and 780 torr.
- Determined that the speed of sound in air remains fairly constant between 400 torr and 780 torr.

For future experimentation, a few changes should be made to the experimental assembly. In order to prevent gas leaks from inside the tube, all of the plastic tubing should be replaced with metal tubing. The tube should become able to be pumped down to pressures lower than 149 torr. Additionally, the end of the tube that is currently sealed off should be replaced with a supply line connecting to various storage vessels so that the specific heat ratio of other gases may be determined. I also recommend the addition of insulated heating tape to the outside of the copper tube. Doing this will allow for the temperature inside the tube to be high enough such that any water-based propellants will not condense inside the tube. With regards to the MATLAB script, I recommend that a feature be included that accounts for the molecular weight and bulk temperature of the gas inside the tube. This way, the specific heat ratio of the gas could be calculated using the same post-processing script that determined the speed of sound in the gas. Finally, the MEMS microphones utilized in this experiment are slightly outdated. I suspect that upgrading these microphones to MEMS microphones with a higher sensitivity will allow for both the speed of sound in a gas and the corresponding specific heat ratio to be determined at lower pressures.

APPENDIX A

LabVIEW Programs

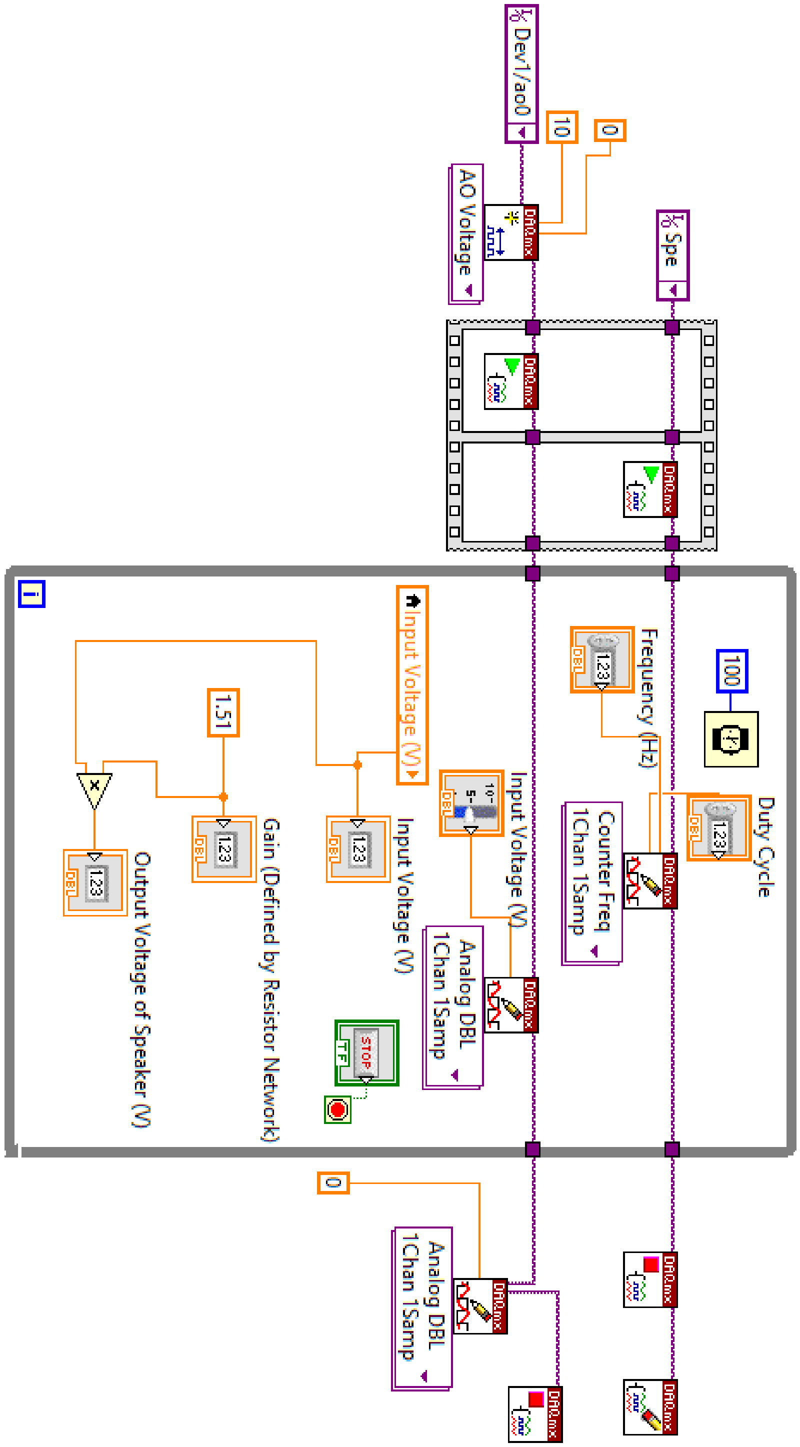

Figure A.1: *Gain Control.lvm* Program Block Diagram

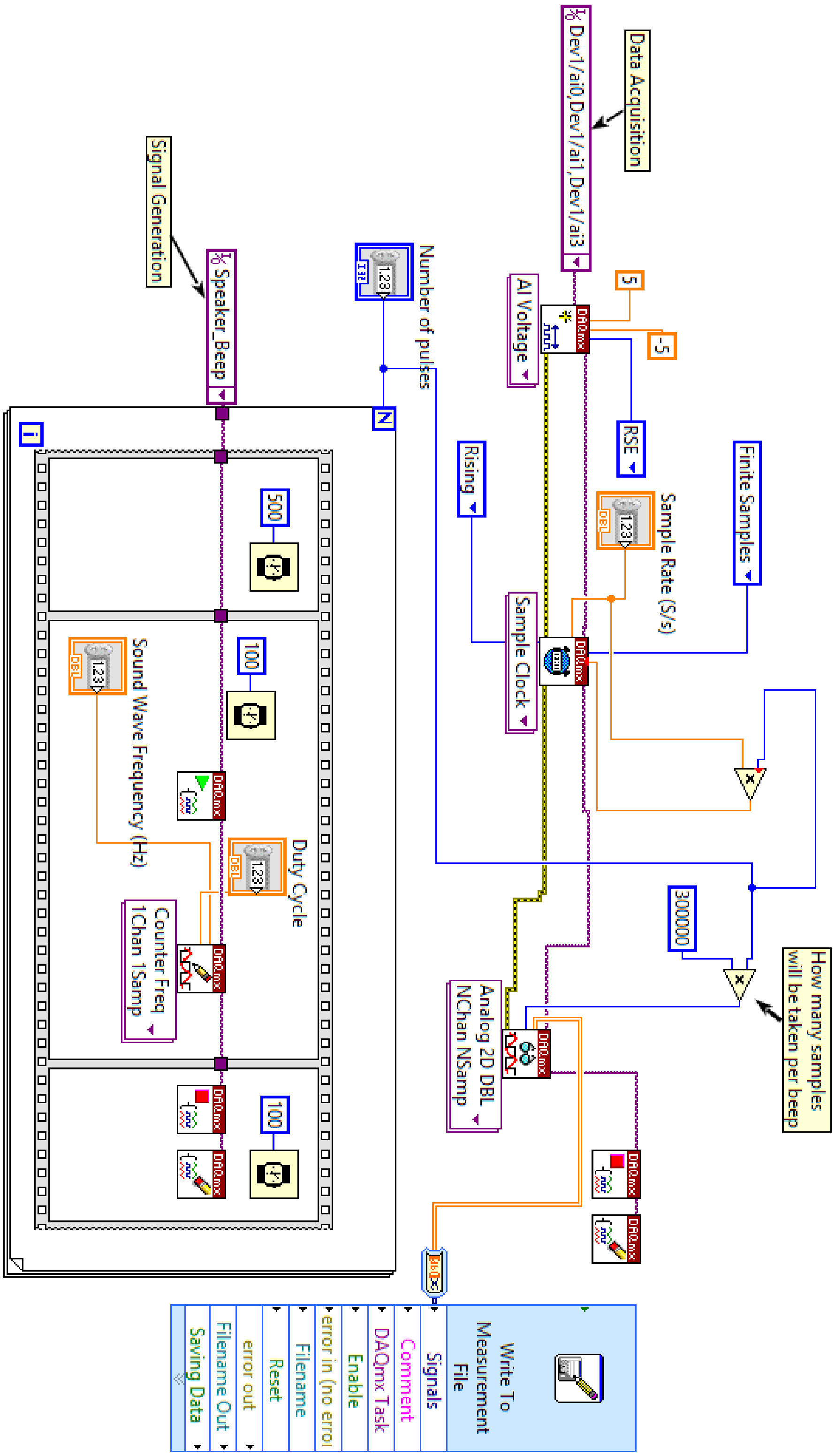

Figure A.2: *Time of Flight v8.lvm* Block Diagram

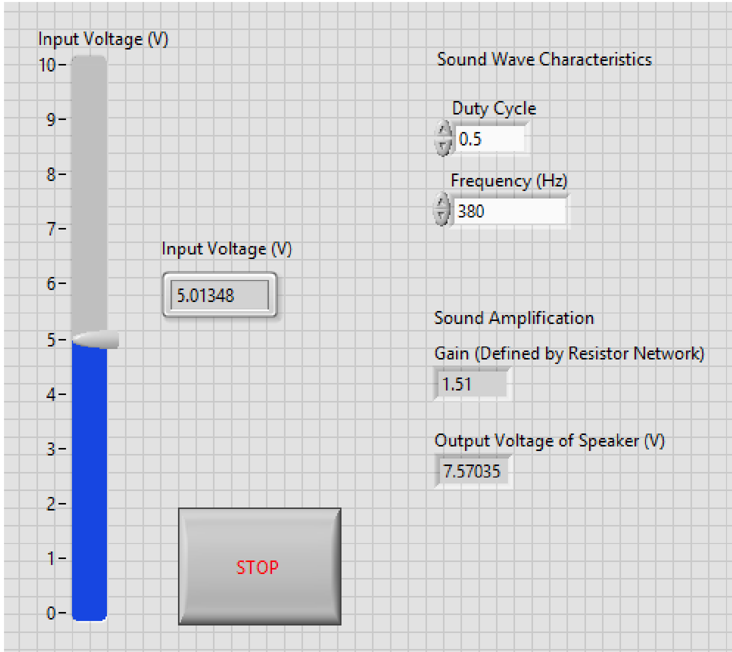

Figure A.3: *Gain Control.lvm* Program Front Panel

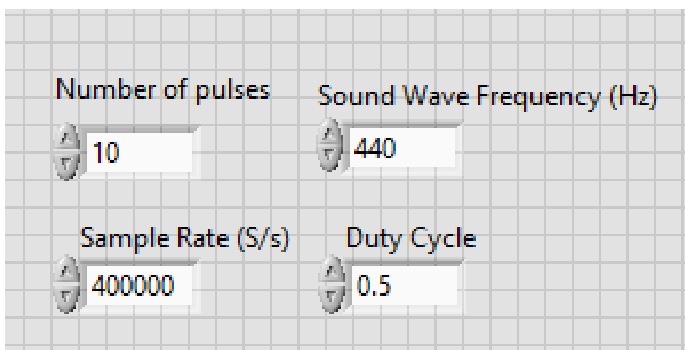

Figure A.4: *Time of Flight v8.lvm* Program Front Panel

APPENDIX B

MATLAB SCRIPT

The following script was utilized for all data post-processing:

```
%Raw data must be converted from .lvm to .txt!

clear all
hold off

data=textread('TimeOfFlight_16-03-21_1043_001.txt'); %Import full data set

sn=data(:,1); %Index column matrices
sp=data(:,2);
ma=data(:,3);
mb=data(:,4);

P=sp-2.4;   %Shifts speaker voltages down so that negative=="off,"
positive=="on"

%Set parameters for ensemble averaging
f=400000;           %Sample rate in Hz (defined by user in ToF v8)
width=f/10; %How many samples to skip while searching for speaker "on" values
bin_size=f/100;     %How many samples to average for each microphone after
speaker turns on

%Find the first time speaker turns on
P(P>0)=1;
P(P<0)=0;
X=find(diff(P)~=0); %Finds all values corresponding to a switch from
                    %off to on or from on to off
Y1=find(diff(P)~=0,1,'first'); %Finds the first time the speaker turns on

on1=Y1(1,1); %Sample number of first "on" value

%Find the rest of the times the speaker turns on
on_X=find(diff(X)>width);
beep=size((on_X),1)+1   %Number of times it beeped, accounts for on1
on=X(on_X+1);    %Sample numbers for each time the speaker turns on (except
for the first time)

A_ma=zeros(bin_size,beep);   %Pre-allocation step
A_mb=zeros(bin_size,beep);   %   "

data1=data(on1:on1+bin_size-1,1:4);
index1=data1(:,1)-data1(1,1);
ma1=data1(:,3); %Creates ma1 and mb1 based on "on1"
mb1=data1(:,4);
```

```
A_ma(1:bin_size,1)=ma1;
A_mb(1:bin_size,1)=mb1;

index=1:bin_size;    %Size of these column vectors is picked by user

i=1:beep-1;
for i=1:beep-1;
    A_ma(1:bin_size,i+1)=data(on(i):on(i)+bin_size-1,3);
    A_mb(1:bin_size,i+1)=data(on(i):on(i)+bin_size-1,4);
end

%Performs ensemble averaging step
ma_ave=mean(A_ma')-mean(ma');
mb_ave=mean(A_mb')-mean(mb');

%Shifts voltage responses down so that they are symmetric
%about the x-axis
C=ma_ave-mean(ma_ave');
F=mb_ave-mean(mb_ave');

%Finds the range of values on which to search for the first
%voltage peak of microphone A

C_D(C>0)=1;  %Assigns a value of 1 to any voltage greater than 0 ("on")
C_D(C<0)=0;  %Assigns a value of 0 to any voltage less than 0 ("off")
C_E=find(diff(C_D)~=0,2,'first');
C_on=C_E(1,1);
C_off=C_E(1,2);

%Finds the range of values on which to search for the first
%voltage peak of microphone B

F_D(F>0)=1;
F_D(F<0)=0;
F_E=find(diff(F_D)~=0,2,'first');
F_on=F_E(1,1);
F_off=F_E(1,2);

%Finds the peak voltages of both microphones

ind=C_on:C_off;
ind1=F_on:F_off;
for i=C_on:C_off;    %Find peak voltage of mic1 and sample # of peak
    [M,Ip]=max(C(ind));
end
for ii=F_on:F_off;  %Find peak voltage of mic2 and sample # of peak
    [N,Jp]=max(F(ind1));
end

J=ind1(Jp)         %Sample number of first peak of mic2
I=ind(Ip)          %Sample number of first peak of mic1
t=abs((J-I)/f);     %Computes the time delay between peaks
L=0.6291;          %Distance between the two mics (m)
```

```
c=L/t               %Computes the speed of the sound wave in m/s

%Plots averaged data sets
hold on;
p1=plot(C,'.');
p2=plot(F,'.');
title('Ensemble-Averaged Microphone Responses');
xlabel('Normalized Sample Number');
ylabel('Voltage (V)');
p1.LineWidth=1;
p2.LineWidth=1;
```

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

a	speed of sound (m/s)
f	sampling rate (kHz)
g_0	gravitational acceleration (m/s^2)
I_{sp}	specific impulse (s)
k	specific heat ratio
L	distance (m)
M	molecular weight (kg/kmol)
R	gas constant (J/kg-K)
S	sample number
T	temperature (K)

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